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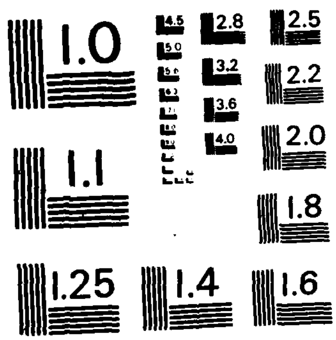

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This final technical report summarizes studies of data on ocean dynamics along the Aleutian Island chain.

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Final Technical Report

Sea Level Variations and Ocean Dynamics In The Aleutian Islands N0001481-K-0684

Duncan Carr Agnew

1.0 Introduction

The overall purpose of this project was to study ocean dynamics along the Aleutian Island chain, which is the boundary between the North Pacific Ocean and the Bering Sea. These two bodies of water communicate through a number of straits (usually called passes) which are shallowest at the eastern end (a list is given in Favorite, 1967). The specific goal of this project was to use pre-existing data sets, particularly long time series of sea level and meteorology, to understand something of the physical oceanography of the area. Particular questions of interest included:

> Tidal dynamics: how do the tides propagate along the chain and through the passes? Why is there an anomalously small S_2 tide in the Bering Sea? What is the flux of tidal energy into the Bering Sea, and how is it distributed along the chain?
>
> Other sea level variations: how does atmospheric forcing affect low-frequency sea level changes? Are other low-frequency signals present that could be correlated with shelf waves or with changes in currents such as the Alaskan Stream (Favorite *et al.*, 1976) near the island chain? Is there any nonlinear interaction between tides and sea level? Can any pattern of meteorology be associated with the harbor seiches observed in some of the tide records?

Largely because of delays in obtaining data, but also because developing the necessary analysis routines took longer than anticipated, not all of these questions were examined during the contract period. This report presents what results were obtained; in all cases they are preliminary rather than final. In many instances they are probably close enough to the truth that some conclusions can be drawn from them.

2.0 Data Collection

Part of the initial impetus for this work was the knowledge that much data had already been collected along the Aleutian chain, sea level data by the National Ocean Survey and meteorological data by various organizations (Figure 2.1). While it is undoubtedly cheaper to use such data than to gather it originally, the initial work required (acquiring the data, putting it into machine-readable form, and checking it) turned out to take far more time than anticipated. The purpose of this section is to discuss what data were gathered and describe some of the bigger pitfalls inherent in them.

Long time series of meteorology are available from several stations and were obtained on magnetic tape from the National Climate Center in TDF-14 format. Table 2.1 lists the stations and Figure 2.2 shows the time periods covered. Some of the early data are hourly values and most of the later data every three hours; at some stations (e.g., St. Paul Island) the sampling is more irregular. These data are generally not difficult to use, but do have several flaws:

1. Some large spikes from transcription or punching errors are present. This can be proved by the occasional differences between the sea-level pressure and station-level pressure series (the latter is computed from the former) and may be suspected in the other series. These are easy to catch in those that are smooth (e.g., pressure) and frequently sampled; in more irregular series (e.g., wind speed) they are not.

2. At frequencies above 3 cpd the two pressure series are not coherent, suggesting that the largest source of energy in this band is reading error and roundoff in the tabulations.

3. The times used in these data are local time, which may be 10 or 11 hours away from Greenwich. The correction usually has to be done on the basis of internal evidence, either that observations (when not hourly) cluster about the standard synoptic times or have a phase shift for the atmospheric tide consistent with some other station. The time corrections deduced are given in Table 2.1.

Long-term sea-level records, made by standard recording gauges, were available from three stations. The original plan was to obtain copies of the original tabulations from the National Ocean Survey (NOS) and have them keypunched. The copies had been ordered, before the start of this contract, by Dr. D. Luther of SIO under an NSF grant; it was agreed that he would provide these in return for having this contract pay for the data entry. Some of this was in fact done, but the long delay in receiving copies of the tabulations meant that nor

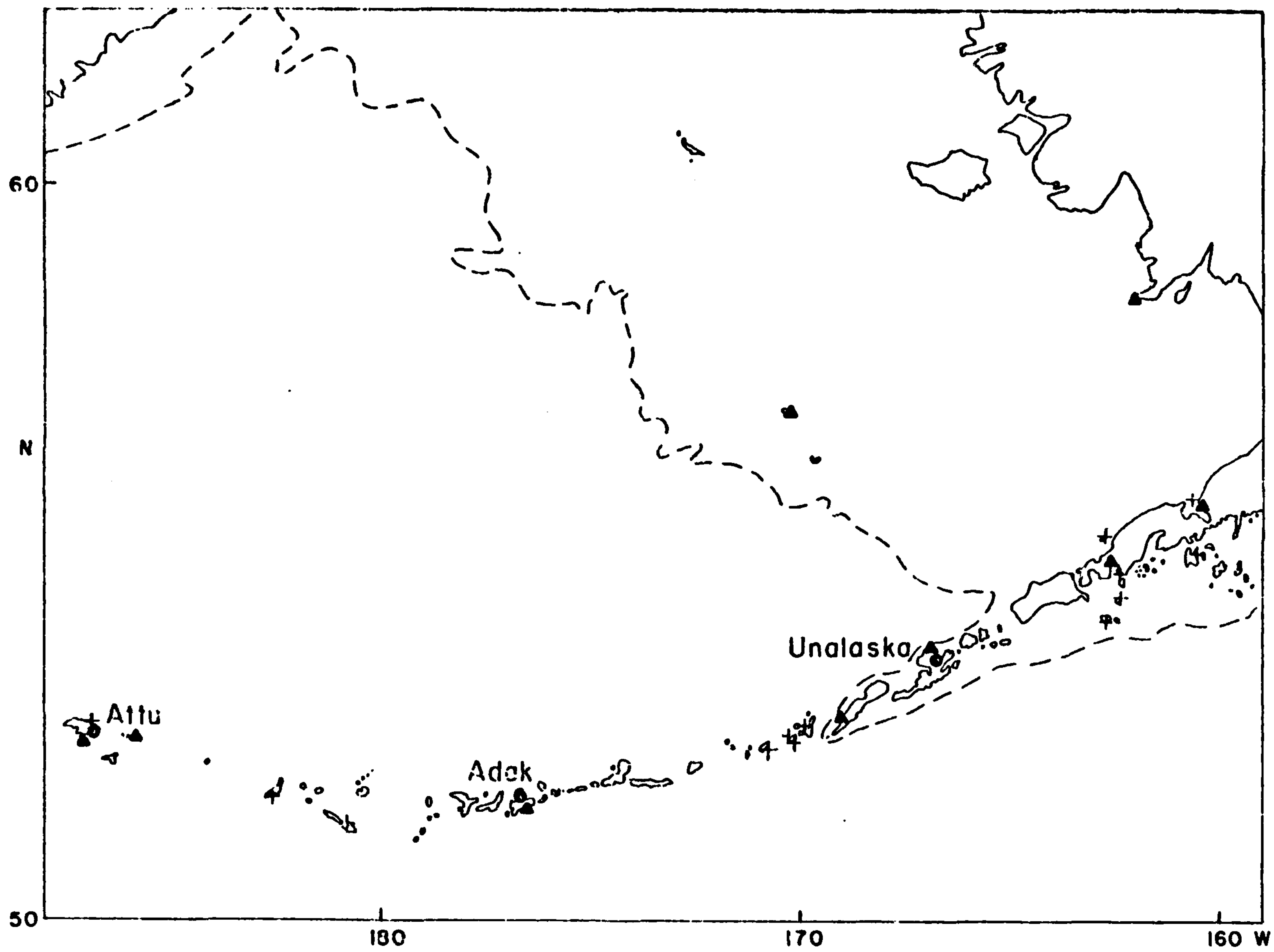

Figure 2.1. Map of the Aleutian chain, showing locations of permanent tide stations (circles), weather stations (triangles) and short-term sea level records (crosses). The dashed line shows the shelf edge.

Table 2.1
Stations Supplying Long Data Sets

#	Name	Lat	Long	Data Type	Time Correction to GMT (hr)
1	Attu	52.84	173.2 E	Meteorology	11
				Sea level	11
2	Shemya	52.72	174.1 E	Meteorology	11
3	Adak	51.8	176.65W	Meteorology	11
				Sea level	11
4	Nikolski	52.92	168.83W	Meteorology	11
5	Driftwood Bay	53.97	166.83W	Meteorology	10
6	Unalaska	53.88	166.54W	Sea level	11
7	Cold Bay	55.5	162.72W	Meteorology	11
8	Port Mollor	55.99	160.56W	Meteorology	11
9	Cape Newenham	58.40	162.10W	Meteorology	11
10	St. Paul Isl.	57.15	170.87W	Meteorology	11

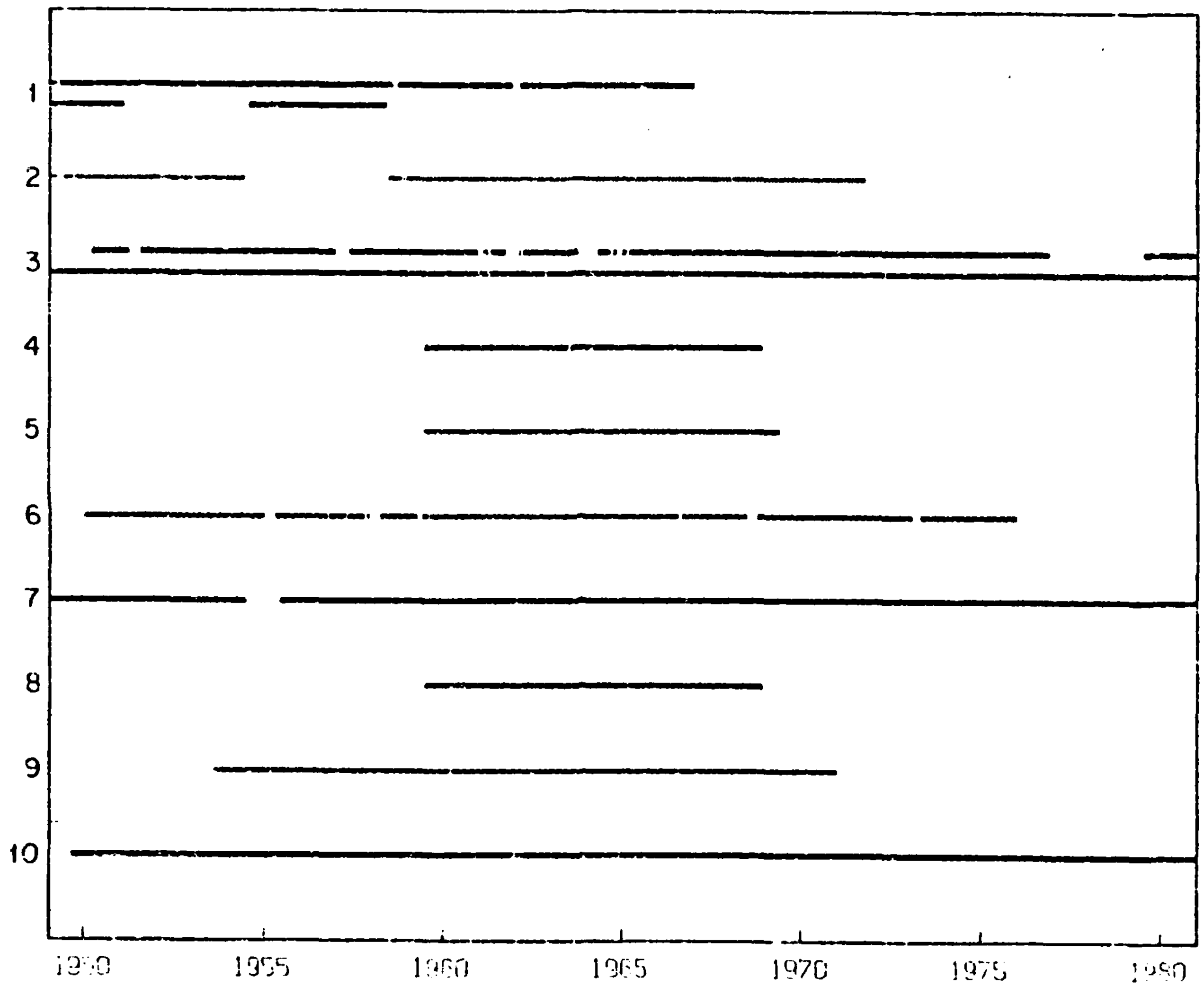

Figure 2.2. Time periods covered by long-term data. The numbers are those given for the stations in Table 2.1. Where two lines are shown the upper is for sea level, the lower for meteorology.

very much had been completed when it was discovered that most of the data had in fact been entered on tape by NOS. Although these tapes have a fair number of errors the presence of checksums makes correction of these errors possible. Work on this was in progress at the end of the contract period; the results given below are based on the data that had already been keypunched and on some series already available in the IGPP Geotape library. For the study of harbor seiching data from the NOS digital "Mitron" tape were obtained, though there proved to be less of this than expected (two years at Sweeper Cove, two years at Sand Point), and there was a timing error on the Sweeper Cove tape (notice of which was sent to NOS).

Over 100 other tide stations are listed by NOS for the Aleutian chain; data were requested for two-thirds of these. Most of these are short-term stations established during hydrographic surveys, and in many cases only high and low waters were tabulated. Data were received for 41 stations, at 14 of which hourly heights were available. All these data have been keyed-in, and the hourly height data edited and transferred to an archive format. This has not been done for the high and low water data because the programs for analyzing them are not yet complete. Data for 24 stations have not yet been received from NOS.

At two of the control tide stations (Sweeper Cove and Unalaska) daily measurements are made of water temperature and density (from which salinity is computed). Copies of the tabulations have been obtained from NOS and keypunched where legible. Some of the data after 1975 are available in machine-readable form. NOS has provided their error-checking software but it has not been converted to the local system.

Current data, also obtained from NOS, are available for some passes along the chain. Most of the measurements were made with Roberts radio current meters (Knox, 1956) for periods of a few days, though some records run for as long as one month. The data available are written direction and plotted speed. These could not be keypunched commercially, so software was written to allow direct entry to our local computer, which was done by a undergraduate student employee (Mr. Vic Lemas). Some of the records are very noisy (probably because of seaweed fouling the meter propeller) and work to deal with this is still in progress.

3.0 Tides and Seiches

A preliminary analysis of sea level data from stations having hourly height data was made using a least-squares harmonic analysis method. The analysis program fit a small number of tidal constituents to the data, allowing for any gaps. A parallel analysis was also made of the local tide-raising potential for the same time interval; the difference in phase between these two analyses gave the local phase, from which the Greenwich phase given in Table 3.1 can be found. The parallel analysis of a reference series corrects, to first order, for the interference between constituents that occurs in a short series.

The results are given in Table 3.1 for the two largest constituents that can be reliably analyzed from a short data set. The amplitudes have not been corrected for nodal modulation, as this does not much exceed 10 percent. The order is from west to east along the chain. East of Unalaska there are no large passes and so the stations may be unambiguously separated into those in the Bering Sea (946-) and those in the Gulf of Alaska (945-). Tidal constants for some of the stations in this table are given in the list published by the International Hydrographic Bureau; the results given here agree with the published values, confirming the reliability of the analysis.

The amplitude and phase of the M_2 tide appears to be nearly constant along the Bering Sea side of the chain as far east as Unalaska. East of this point, moving over the shelf and into Bristol Bay, the amplitude grows and the phase changes rapidly, as described in more detail by Pearson et al. (1981). On the Pacific side of the Aleutians the phase varies from 100° at the western end to -30° south of the Alaska peninsula. Since the depth profile does not vary much along this side of the chain, the tide must propagate along it at a fairly constant speed; the phase difference along the two sides will thus be greater the farther east we go. Some indication of this is given by the four stations in the central Aleutians: N. Yunaska and Applegate Cove are on the Bering Sea, and have phases near 60°, while Herbert and E. Yunaska face more on the Pacific and have a more negative phase. The rapid phase shift in this small distance is of course responsible for the large tidal currents in the passes, discussed in more detail in Section 5 below.

Even though only four years of records were used, it proved possible to make a meaningful analysis of the long-period tides, because the high coherence of sea level with barometric pressure (Section 4) allowed the noise to be reduced to a low level. M_2 tidal amplitude and phase were found by least-squares fitting to a record corrected for pressure effects, and computing the admittance relative to a self-consistent equilibrium tide (Agnew and Farrell, 1978). The results are

Station	Amplitude	Phase
Massacre Bay	1.10 ± .20	$0^\circ \pm 10^\circ$
Sweeper Cove	1.15 ± .06	$-7^\circ \pm 3^\circ$
Unalaska	1.18 ± .33	$35^\circ \pm 16^\circ$

Table 3.1
Aleutian Islands Tides

Station, NOS number	Lat (N)	Long	Record Length (d)	M_2 amp	M_2 ph	O_1 amp	O_1 ph
Steller Cove 946-0111	52.99	172.9 E	10	20	80	28	135
Massacre Bay 946-0150	52.84	173.2 E	1214	22	98	22	-40
Alcan Hbr. 946-0256	52.73	170.07E	29	21	101	25	-38
Gertrude Cove 946-0674	51.94	177.46E	20	20	65	28	-45
Constantine Hbr. 946-0898	51.41	179.28E	421	15	64	21	-42
Sweeper Cove 946-1380	51.86	176.65W	1461	19	84	33	-49
Yunaska Isl., N 946-2144	52.68	170.71W	44	24	50	23	-62
Yunaska Isl., E 946-2161	52.66	170.56W	30	21	18	23	-56
Herbert Isl. 946-2205	52.72	170.17W	8	36	10	22	-78
Applegate Cove 946-2239	52.86	169.86W	115	25	62	24	-61
Unalaska 946-2620	53.88	166.54W	1675	27	81	19	-53
St. Catherine Cove 946-2944	55.01	163.51W	30	27	87	23	-61
Amak Isl. 946-2987	55.41	163.12W	74	71	131	31	-47
Cherni Isl. 945-9893	54.63	162.37W	58	63	-30	22	-92
King Cove 945-9881	55.06	162.32W	521	69	-32	22	-90
Port Mollor 946-3502	55.99	160.56W	92	109	209	36	-18
Sand Point 945-9450	55.34	160.50W	720	76	-38	21	-89

Amplitudes in cm; phase is Greenwich (G), in degrees

The admittance amplitudes are slightly, though not significantly, above equilibrium; the same result found by Cartwright (1968) for the eastern North Atlantic, though not by Wunsch (1967) for the equatorial Pacific.

Spectra of the six-minute data (after removing the tides) from Sweeper Cove and Sand Point are shown in Figures 3.1 and 3.2. Because of the substantial averaging (made possible by the long records available) the statistical uncertainty is only ± 1 dB; hence nearly all the peaks seen are significant. The complex coastline around these two stations apparently makes possible a very large number free modes of oscillation. Many of the periods are so long th the disturbances must be very large scale; detailed modeling uld obviously be a formidable task. In one sense these spect are somewhat misleading, since an examination of a suitably b passed time series shows this energy to be anything but stationary. .c' in analysis of the Sweeper Cove data showed that much of the rgy in the 1-2 cph band occurs in large bursts. These did not, however, appear to correlate with particularly low pressures or high winds, to judge from the meteorological data on tape.

4.0 Sea Level and Meteorology

The sea level data available limited comparison of sea level and weather to the periods 1959-64 for Unalaska, 1967-71 for Adak, and 1954-59 for Attu (see Figure 2.1 for the locations of these stations). Pressure and wind records are available for Attu and Adak; the closest weather station to Unalaska is at Driftwood Bay, 25 km away. Weather data are also avaiable from five other stations in the eastern Aleutians, from 160 to 500 km from Unalaska (Table 2.1).

A cross-spectral study (in the manner of Wunsch (1972)) gave a simple result: at the three places studied, sea level response to atmospheric pressure changes nearly as an inverted barometer. An exact inverted barometer response means that as pressure rises sea level falls at the hydrostatic rate of 1.01 cm/mb. Such a response is common at islands, but not necessarily along coasts. Attu and Adak both show similar responses: the coherence between air pressure and sea level is zero at frequencies above 3 cycles per day (cpd), becoming sigificant in the intertidal band between 1 and 2 cpd, and substantial below 1 cpd. The phase is a nearly constant 180°, and the admittance amplitude gradually rises, approaching the hydrostatic level at the lowest frequencies analyzed (about 1 cycle per month). Figure 4.1 shows the response at Adak. Unalaska is in a more "coastal" environment, but its response (Figure 4.2) is very nearly the same as at the other two stations, though there is a suggestion of a systematic change in phase with frequency. The coherence at Unalaska is also

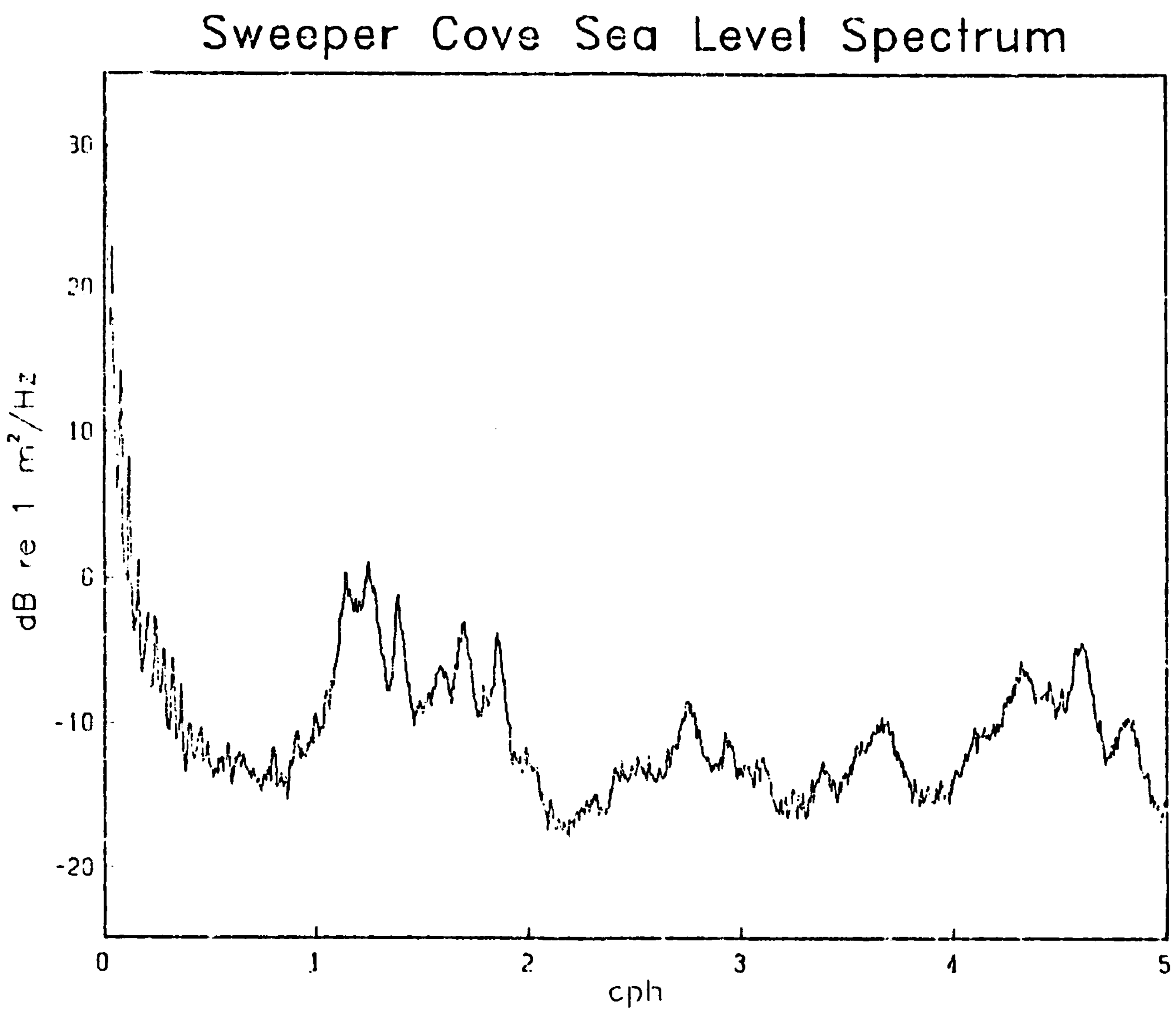

Figure 3.1. Spectrum of sea level (after removing tides) from the NOS digital tide gauge at Adak, Alaska, for the time period 1979:200-1981:304.

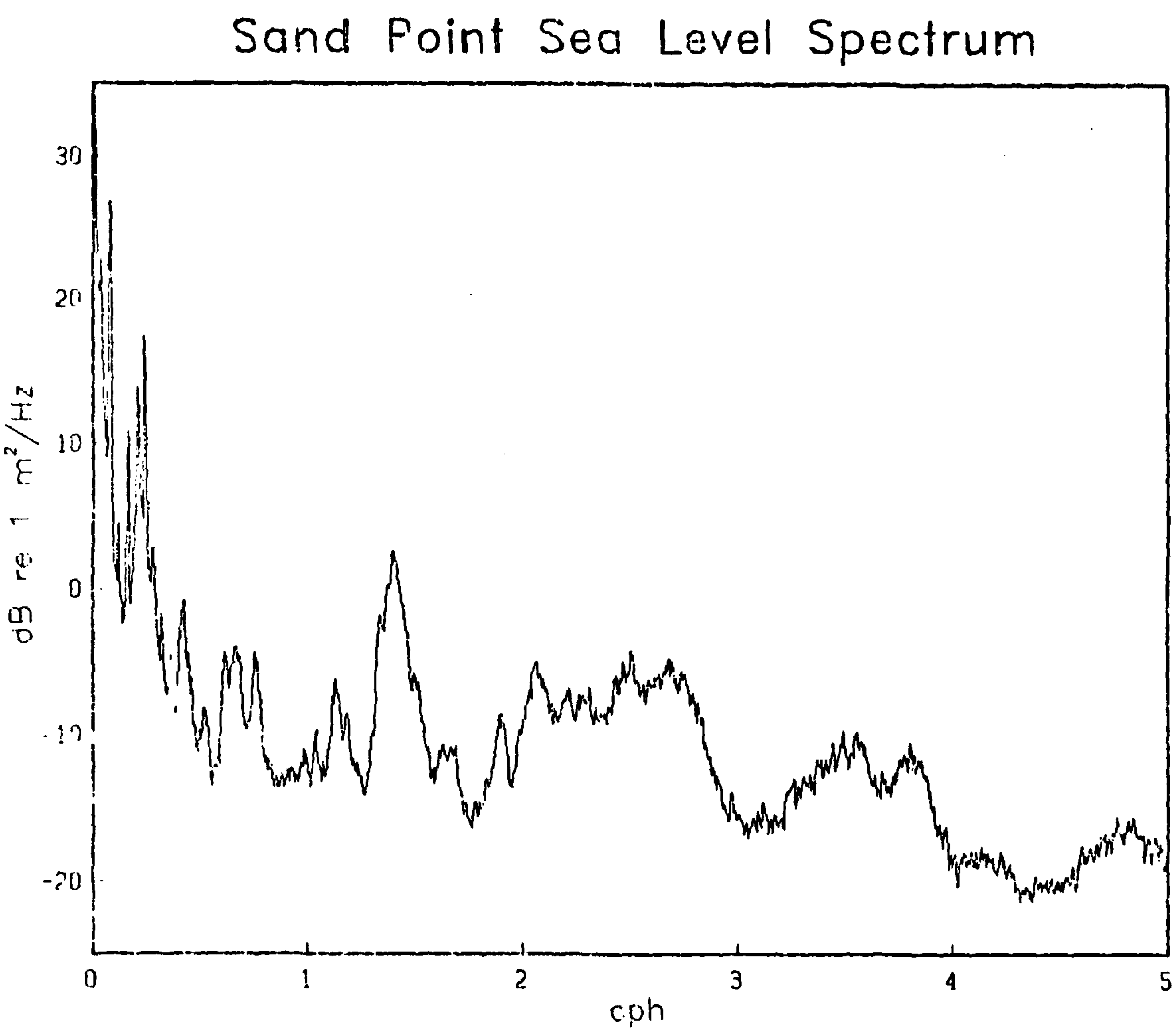

Figure 3.2. Spectrum of sea level (after removing tides) from the NOS digital tide gauge at Sand Point, Alaska, for the time period 1979:4-1981:3.

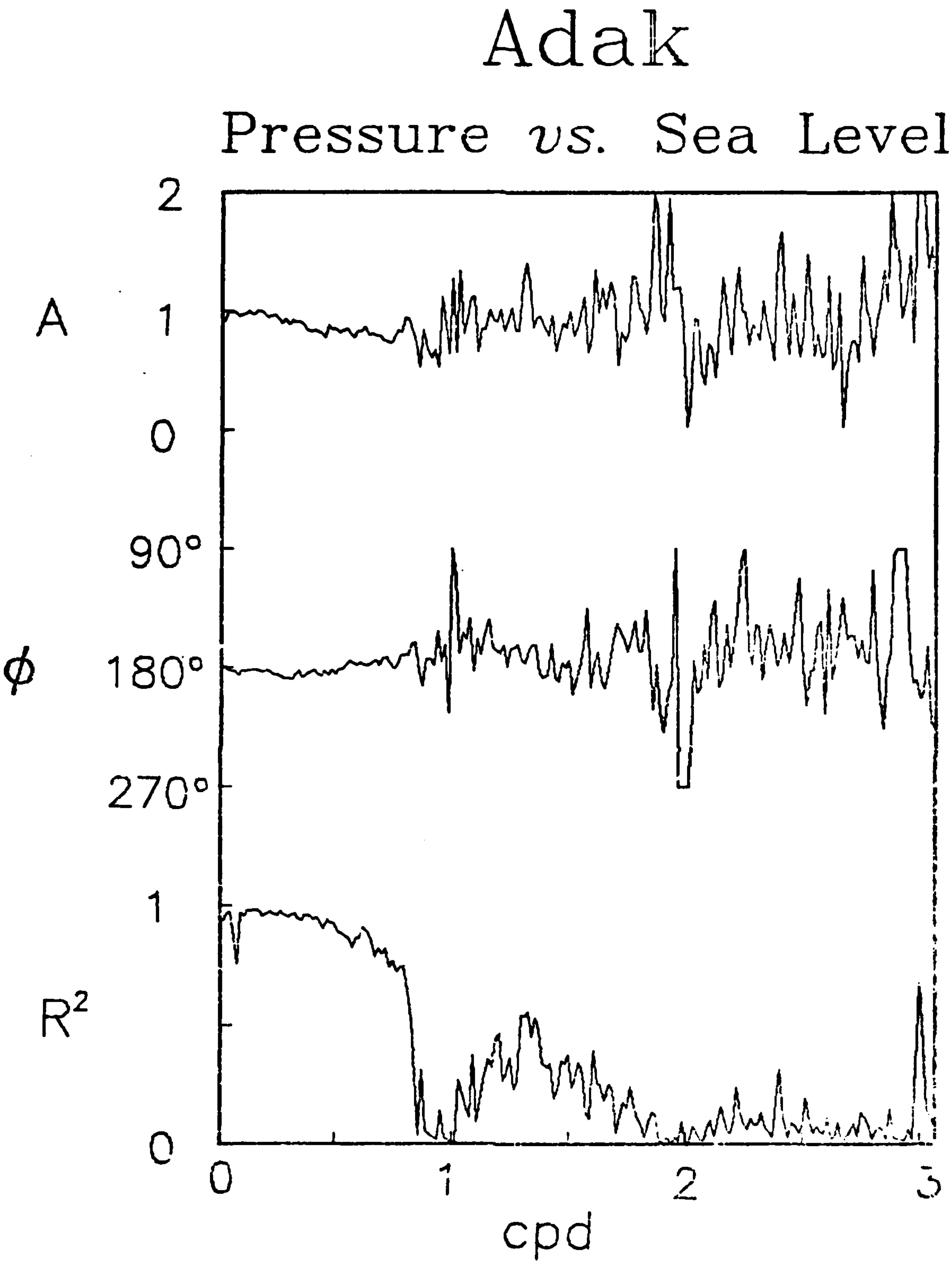

Figure 4.1. Results of cross-spectral analysis between air pressure and sea level at Adak, for frequencies between 0 and 3 cycles per day. Bottom trace is coherence squared, middle phase angle of the admittance (clipped to fall between 90° and 270°) and top amplitude of the admittance.

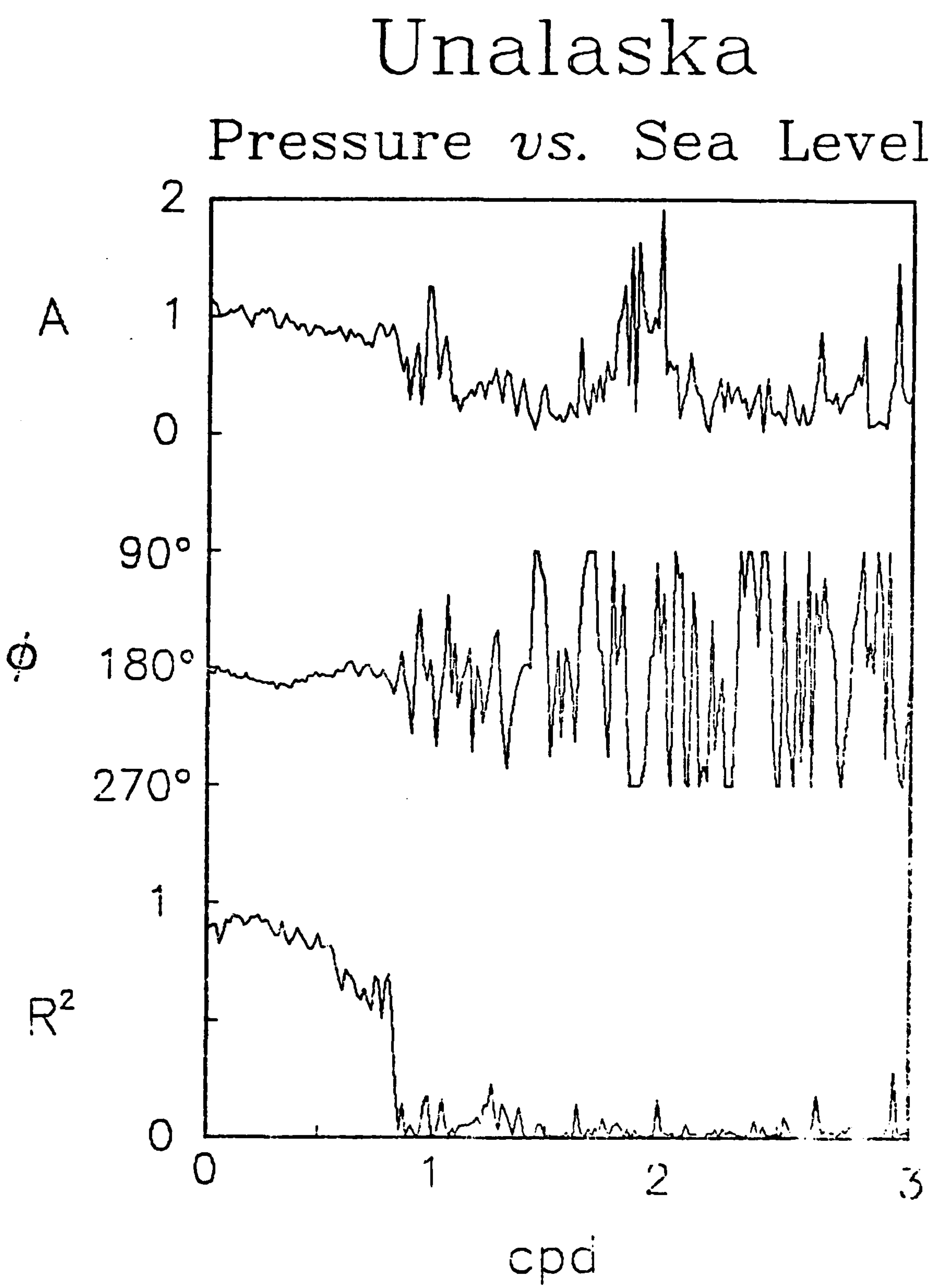

Figure 4.2. Results of cross-spectral analyses between air pressure at Driftwood Bay and sea level at Unalaska. See Figure 4.1 for details.

lower, but this probably reflects the greater separation between the places where sea level and pressure were measured. The low coherence above 2 cpd is not surprising given the high noise found in the barometer data at these frequencies (Section 2). Below 1 cpd the power in the pressure signal, the length scale of pressure variations, and the coherence with sea level all rise. Cross-spectra between pressure records show that at frequencies below 1 cpd pressure changes are coherent over distances up to 400 km, with the coherence falling steadily from 0 to 1 cpd. This decrease in length scale with increasing frequency may partly explain the slight departure of the sea level response from that of an inverted barometer. That the departure is so slight suggests that shelf-wave dynamics (Myzak, 1980) are not very important along the Aleutian arc.

Cross-spectra of local North and East wind with sea level showed no coherence that could not be explained by the coherence of wind with pressure. In particular, the wind remains incoherent with sea level at the lowest frequencies (.3 to 1 cycle per month), where the coherence of sea level with pressure is decreasing. This result differes from that of Wunsch (1972), who found wind to be more coherent with sea level than air pressure at periods from 1 month to 1 year. However, Chelton (1980) found that wind stress was not very coherent with sea level in the Aleutians at frequencies below 6 cycles per year.

5.0 Tidal Energy Flux

One item of particular interest in this project was the question of the size of the tidal energy flux into the Bering Sea. A number of early estimates of tidal dissipation on hte Bering Sea shelf indicated that a great deal of energy (up to 750 GW) was dissipated there. Miller (1964, 1966) estimated the energy flux through the Aleutians and into the Bering Sea to be 240 GW. However, detailed tidal models (Sundermann, 1977) gave a dissipation on the shelf of only 29 GW, and a flux calculation using pelagic tide height and current measurements (Pearson and Mojfeld, 1980) gave a flux onto the shelf of 20-30 GW. Since there is nowhere else known in the Bering Sea to dissipate large amounts of tidal energy there is an obvious discrepancy with Miller's values, and it therefore seemed worthwhile to check (and perhaps improve) these by working from the original data rather than with the published constants.

If we take the equations of motion and continuity for a fluid and assume (as is usual in tidal calculatons) that the velocity is independent of depth, the energy balance equation for a region is

$$\int_M E \cdot n \, ds = \int_A hu \cdot f \, dA + \int_A \rho g \tilde{\zeta} \dot{\zeta} \, dA$$

This says that the energy flux through the margin equals the amount dissipated through friction f acting against velocity u in depth h plus the flux out through astronomical forcing as expressed by the interaction between the equilibrium potential $\tilde{\zeta}$ and the surface elevation ζ. The energy flux vector is

$$E = \rho g h u(\zeta-\tilde{\zeta}) + \tfrac{1}{2}\rho h|u|^2 u$$

where ρ is the density of seawater and g the local acceleration of gravity. If we suppose $\zeta-\tilde{\zeta}$ to be sinusoidal with amplitude A, and u (in a direction normal to the boundary) to be sinusoidal with amplitude U and phase ϕ relative to $\zeta-\tilde{\zeta}$, the net flux in that direction over one cycle is

$$\langle E\rangle = \tfrac{1}{2}\rho g h A U \cos\phi \tag{5.1}$$

Miller's procedure was to use the formula

$$\langle E_m\rangle = \tfrac{1}{2}\rho g A U \cos\phi$$

where A and ϕ referred only to the amplitude and phase difference of ζ. This gives a flux per unit area, which when multiplied by the area of the passes will give the tidal flux. I have instead used (5.1) because it includes the depth explicitly. As the tides propagate through the passes the depth changes substantially, and use of an areal flux rate computed at one depth and an area based on another could lead to large misestimation of the total flux. In the absence of lateral refraction the flux per unit length will remain constant. For each current station used the current amplitude and phase were estimated by least-squares fit of the largest tidal harmonic to the data, resolved into directions parallel and perpendicular to the axis of the pass. The quality of the fit could be judged by the variance in the raw and residual series; a dataset for which the harmonic fit did not give a large reduction of variance was judged to be noisy and was not used. The depth was estimated from local charts; the amplitude and phase of the local tide were chosen roughly on the basis of the data described in Section 3; the forcing potential $\tilde{\zeta}$ was taken to be 70 percent of the equilibrium potential, ignoring loading contributions.

Table 5.1 lists the results, which are plotted in Figure 5.1. For each entry the table gives the relevant pass, the station name (used at

Table 5.1
M_2 Tidal Fluxes

Pass	Station Name	Lat, Depth,	Long, Azimuth	M_2 Constants Along	Across	Height	Flux (MW/km)	Distance (km)
Akutan	Boothe 14	54.02,	166.05W	2.6	.6	.25	77	37
		55m,	-61°	9	27	-40		
Akutan	Boothe 15	53.98,	166.07W	2.1	.3	.25	50	39
		46m,	-61°	10	172	-4		
Unalga	Boothe 16	53.95,	166.20W	2.1	.4	.25	23	44
		22m,	-55°	11	-160	-10		
Umnak	Boothe 18	53.36,	167.81W	1.1	.3	.25	72	49
		64m,	39°	-9	106	-10		
Umnak	Boothe 18B	53.38,	167.84W	.9	.1	.25	40	51
		45m,	25°	4	152	-10		
Fenimore	Mast 48	51.97,	175.56W	1.5	.2	.25	40	250
		37m,	-8°	16	24	-20		
Chugal	Nelson 37	51.95,	175.97W	.6	.2	.25	26	262
		55m,	-42°	-25	-54	-50		
Little Tanaga	Grenell 25	51.82,	176.24W	1.2	.5	.25	56	268
		55m,	-17°	-4	2	-30		
Adak	Grenell 7	51.79,	177.00W	.7	.1	.25	54	277
		82m,	19°	-32	18	-50		
Adak	Grenell 6	51.79,	177.09W	.2	.1	.25	12	281
		55m,	19°	-29	39	-50		
Kanaga	Grenell 29	51.74,	177.75W	.8	.4	.25	13	289
		18m,	4°	-20	14[illegible]	-50		
Tanaga	Grenell 13	51.65,	178.22W	.7	.4	.25	40	310
		97m,	-14°	10	7[illegible]	-50		
Amchitka	Anderson 26	51.31,	179.[illegible]4W	.5	[illegible]	.25	30	350
		73m,	-12°	-26		-60		
Ogliala	Karo 1	51.[illegible]1,	178.[illegible]3E	.6	.1	.25	33	460
		55m,	37°	-54	-44	-60		
Rat	Karo 3	51.90,	177.90E	1.1	.3	.25	33	490
		37m,	22°	-32	35	-60		

M_2 constants have amplitudes on first line, in m/s or m, and Greenwich phases in degrees on second line.

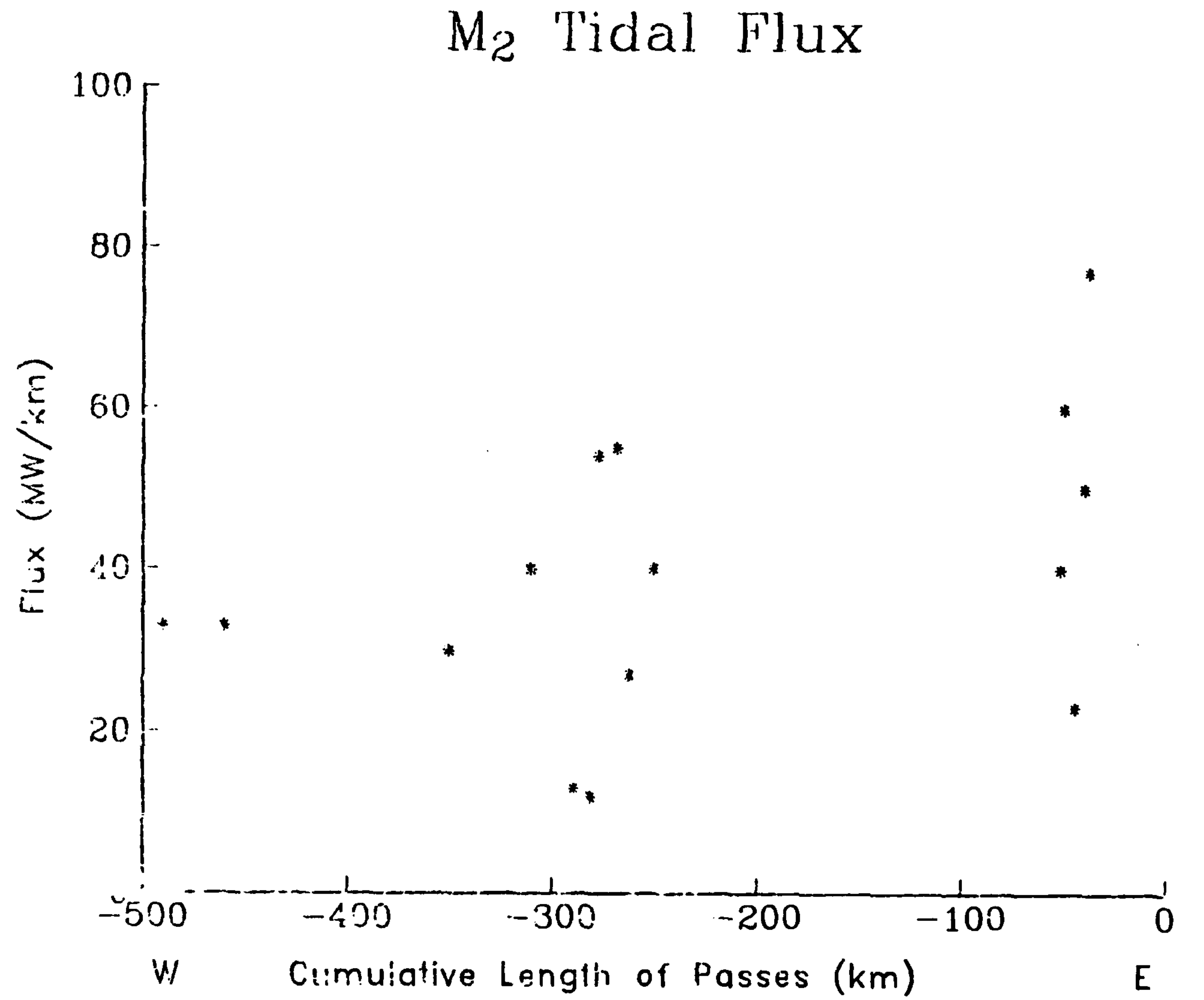

Figure 5.1. Power flux per unit length of the M_2 tide into the Bering Sea along the Aleutian chain; the details are given in Table 5.1. The data are plotted against the cumulative length of open water from False Pass going west.

NOS), the location and depth, the amplitude and Greenwich phase of the M_2 current and sea level tides, and the computed flux. Though there is considerable scatter in the results they suggest an average value of about 30 MW/km. If this holds over the total length of the passes (1300 km) the flux would be 40 GW, not significantly higher than the measured flux onto the shelf. This analysis thus indicates that the flux value proposed by Miller (1966) is indeed much too high. Unfortunately, since the details of his analysis are unavailable, it is not possible to determine the reason for this discrepancy.

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